4.3 ENERGY STORAGE TECHNOLOGIES

Energy storage technologies, especially batteries, have been identified as critical enabling technologies for the successful development of advanced, fuel-efficient, light- and heavy-duty vehicles. The energy storage R&D effort of the FCVT Program is responsible for advancing the state of the art and facilitating the adoption of innovative batteries for a wide range of vehicle applications, including HEVs, battery electric vehicles (EVs), 42-V vehicular systems (42V), and hybrid fuel cell vehicles. The office is working in close partnership with the automotive industry, represented by the United States Advanced Battery Consortium (USABC). The USABC has responsibility for the FreedomCAR and Fuel Partnership Electrochemical Energy Storage technical team.

Development activities are chosen to address energy storage needs identified through interaction between the Electrochemical Energy Storage technical team and the four functional collaboration areas listed in Figure 17. Target development begins by resolving system power needs reported from the technical teams responsible for defining global vehicle systems, specifically the advanced propulsion sub-systems and their components (fuel cells, power electronics, electric motors, and combustion engines). Models and verification efforts aid in resolving system interface conflicts, resulting in component-level technical targets compatible with system expectations.

The vision of energy storage technologies is to enable and support the development of durable and affordable advanced batteries covering the full range of applications from “start/stop” (denoting a vehicle whose ICE is off when the vehicle

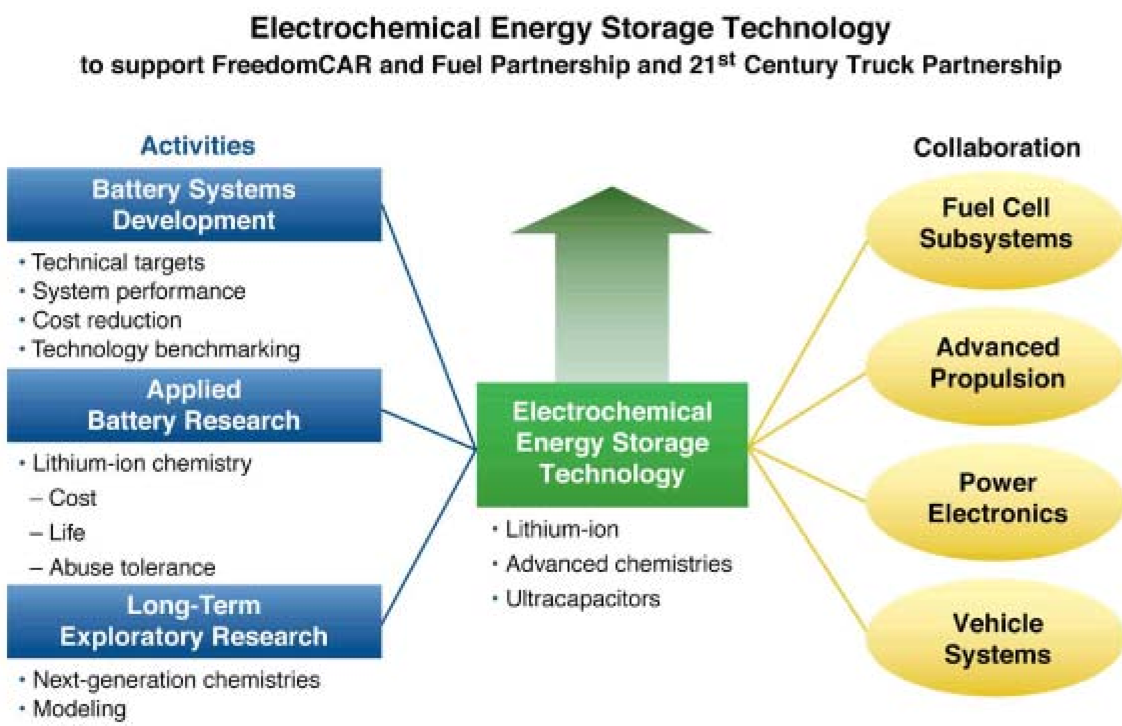

Figure 17. Interaction among the Electrochemical Energy Storage technical team and the collaboration areas.

is stopped) to full HEVs, EVs, and hybrid fuel cell vehicles. In addition, these development efforts will deliver technology that is directly applicable to heavy hybrid vehicle energy storage requirements. These efforts leverage all available resources, including those of automobile manufacturers, battery developers, small businesses, national laboratories, and universities, to address the technical barriers preventing the introduction of battery systems to the marketplace.

Goals

- By 2010, develop electric drivetrain energy storage with a 15-year life at 300 Wh with a discharge power of 25 kW for 18 seconds and $20/kW cost (a FreedomCAR and Fuel Partnership Goal).
- By 2012, develop an energy storage system with a 15-year life and cost ≤$25/kW peak electric power rating (21st CTP Partnership Goal).
- Reduce the production cost of a high-power 25-kW battery (light vehicle) from $3000 to $750 in 2006 and to $500 in 2010 (Priority FCVT Goal defined in Section 3).

Programmatic Status

The energy storage effort has supported battery research for automotive applications for more than 25 years. For most of the early years, its work was primarily focused on validation tasks and on exploratory research, examining and evaluating a wide spectrum of electrochemical couples that showed some promise in electric vehicle applications. Upon the formation of the USABC in 1991, followed by the establishment of the Partnership for a New Generation of Vehicles (PNGV) in 1993, efforts began to focus on the most promising technologies for EV and HEV applications, respectively, with a much heavier emphasis on development.

Battery modules (including $LiAl/FeS_2$, NiMH, Li-ion, and Li/polymer) have been built and tested against EV and HEV targets. Even after significant development, none of these systems was able to simultaneously meet PNGV requirements, especially cost, although modules designed for higher-power applications (HEVs) came closer to meeting or exceeding their performance targets than systems built for higher-energy applications (EVs). The cost of the advanced batteries exceeded the targets by a factor of almost four, on both a kW and kWh basis. The main cost drivers included the costs of raw materials and materials processing costs, cell and module packaging costs, and fail-safe electric and mechanical safety device costs.

In 1997, it was recognized that developers were facing a set of closely related challenges in developing Li-ion batteries, primarily in the areas of calendar life, abuse tolerance, and cost. To address these barriers, DOE collaborated with the U.S. auto companies, via the Electrochemical Energy Storage technical team, to establish a technical support activity at DOE's national laboratories. FCVT consolidated resources and initiated an applied battery research activity, initially called the Applied Technology Development activity. This activity consists of five national laboratories working together with the flexibility to quickly change focus as current obstacles are overcome and new challenges are identified. In 2000, a long-term exploratory research activity was organized around specific baseline systems. Teams of scientists were organized to address six research areas (cell development, anodes, cathodes, electrolytes, diagnostics, and modeling) with resources focused on identifying, understanding, and addressing long-term technical barriers.

Near-term barriers identified during development become subjects for applied research; longer-term barriers are addressed in long-term technology research. The following sections provide highlights of the status of the battery development, applied research, and long-term exploratory research activities.

Battery Development

Battery development is one of the primary activities of the energy storage effort. It is subdivided into three closely related sets of sub-activities: full system development, technology assessment, and benchmark testing.

Full system development. NiMH battery development for EVs was successfully completed in FY 2000. The current task is focused on development and evaluation of a cost-optimized liquid-cooled monoblock HEV module.

The development of an advanced lithium/sulfur (Li/S) system has been initiated. This technology has the potential of meeting all of the EV performance targets; however, it faces several significant technical barriers, including dendrite growth on the lithium, irreversible losses of both lithium and sulfur with aging, and isolation of sulfur in the form of Li_2S as a result of over-discharging. Through subcontracts to the USABC, two long-term R&D projects were initiated to investigate this system. The early phases focus on finding a means to improve the anode-electrolyte interface against parasitic reactions and to improve the cells' cycling efficiency.

Recent work in Li-ion technology for EV applications has focused on addressing the gas buildup in cells, which reduces their useful life, especially at higher temperatures and states of charge. Another focus has been reducing the cost of a full HEV module. The developer delivered complete packs that met all of the FreedomCAR and Fuel Partnership HEV performance targets except cost. Tables 7 and 8 present the current performance status of high-power (for HEV) and high-energy (for EV) Li-ion batteries against technical targets.

Table 7. Performance of high-power Li-ion batteries (2003)

Performance	Current Li-ion	System target
Specific power (W/kg, 18-s discharge)	900	625
Power density (W/L)	1,450	780
Specific energy (Wh/kg)	75	7.5
Cycle life (25-Wh cycles)	300,000	300,000
Calendar (years)	10+	15
Abuse tolerance	Requires thermal and electrical management systems	Inherently safe battery
Low-temperature performance	Degraded power performance at −20°C	25 kW at 18-s discharge
Selling price ($/system at a production volume of 100,000 units/year)	(Approximately 2–4 times the target value)	500

Table 8. Performance of high-energy Li-ion batteries (2003)		
Performance	**Current Li-ion**	**System target**
Specific power (W/kg, 80% DOD/30s)	280[a]	400
Power density (Wh/L @C/3)	155[a]	300
Specific energy (Wh/kg @C/3)	100[a]	200
Power density (W/L)	440[a]	600
Cycle life – 80% DOD (cycles)	1,000	1,000
Selling price: 40 kWh ($/kWh at a production volume of 100,000 units/year)	(Approximately 2–4 times the target value)	100

[a] Battery performance calculated from cell performance by applying a burden factor based on battery design.

Technology assessment. Before entering into agreements to develop full systems (which can span several years and entail a significant cost), technology assessments are often conducted. These limited, 12-month tasks assess a developer's current capabilities and validate technical claims by independent testing. The purpose is to assess the developer's current technology status as well as assess the developer's ability to develop and deliver a full-scale, fully packaged battery. Current assessment tasks include cells based on Li-ion gel technology, a spinel-based chemistry, and a new $LiFePO_4$ cathode active material.

Benchmark testing. Benchmark testing of emerging technologies is important for remaining abreast of the latest industry developments. Working with the national laboratories, FCVT purchases and independently tests hardware against the manufacturer's specifications and the most applicable technical targets. Recently completed benchmark testing included Li-ion/manganese spinel chemistries against HEV and EV targets.

Other Development Activities

Low-cost separator task. Studies at the national laboratories have shown that, for high-power batteries, the cost of non-active material components (packaging, current collectors, and separator) can equal or exceed the cost of the active materials. The current cost of the separator, at $2–3/m^2, represents approximately 30% of the total cost. As a consequence, support is being provided to the development of a low-cost, polypropylene (PP)-based separator using a wet process, an established dry production process applied to PP-based separators, and a nylon-based high-strength low-cost separator. The goal of these tasks is to produce acceptable separators at a cost of $1/m^2.

Ultracapacitors. Current ultracapacitors (symmetric carbon-carbon double layer ultracapacitors) can attain only approximately 50% of the energy density requirements specified in the PNGV battery manual for HEVs in the power-assist mode. In response to recently reported advances, FCVT continues to track and benchmark this technology against technical targets at DOE laboratories. Requirements and test procedures for ultracapacitors are currently being revised in collaboration with the technical team. Note that ultracapacitors may be particularly relevant for heavy-duty hybrid vehicles.

Applied Battery Research

Li-ion systems, currently closest to meeting all of the technical energy storage requirements for vehicle applications, face several cross-cutting barriers that are being addressed through applied battery research.

Five national laboratories participate in this activity, and each brings its own expertise. The major focus areas are

- Battery system development and electrochemical diagnostics
- Battery testing and electrolyte development
- Spectroscopy and microscopy diagnostic, including X-ray diagnostics
- Abuse evaluation, accelerated life test protocol development, and statistical analysis

Long-term Exploratory Battery Research

Long-term exploratory research addresses fundamental problems of chemical instabilities that impede the development of advanced batteries. This research provides a better understanding of why systems fail, develops models to predict system failure and to optimize systems, and investigates new and promising materials. It presently concentrates on six research areas: cell development, anodes, electrolytes, cathodes, diagnostics, and modeling. It focuses on the improvement of three baseline systems and several exploratory systems that are direct extensions of the baselines. The baseline systems are reviewed every two or three years and updated if necessary. The present systems are shown in Table 9.

Table 9. Current baseline and exploratory systems

Systems	High energy	Moderate energy/power	High power
Baseline	Natural graphite/$LiPF_6$ in PC:EC:DMC/$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$	Natural graphite/$LiPF_6$ in PC:EC:DMC / $LiFePO_4$	Natural graphite/LiBOB in γBl:EA/$LiMn_2O_4$
Exploratory	Alloys/$LiPF_6$ in PC:EC:DMC/Layered oxides	Natural graphite/gel/phosphates	Natural graphite/gel/spinels
	Li /X/electrolyte/ layered oxides	--	--
	Li /X/gel/sulfur-based	--	--

In **cell development**, experimental cells incorporating novel materials are prepared and evaluated. For example, several sources of $LiFePO_4$, optimized for rate capability, have recently been acquired and are being evaluated.

Investigators working on **anodes** have developed tin-based intermetallic alloys of Cu, Sb, and Mg. These materials suffer from capacity loss on cycling as a result of structural changes. The search continues for a material that would not exhibit structural changes.

Work on **electrolytes** has mostly focused on solid polymer electrolytes. Cells with a composite polymer electrolyte have been assembled and cycled. Dendrite formation continues to be a major challenge.

Work on **cathodes** has concentrated on two materials, $LiFePO_4$ and $LiNi_xM_y Mn_{1-x-y}O_2$. $LiFePO_4$ is a low-cost, stable, and abuse-tolerant material. $LiNi_xM_y Mn_{1-x-y}O_2$ is a high-voltage, high-capacity material. (Here "M_y" is a generic representation for a metallic element such as cobalt or aluminum.)

Work in **diagnostics** has resulted in tools to help researchers better understand the processes occurring in actual cells. It has advanced the capabilities of Fourier Transform infrared spectroscopy, attenuated total reflectance infrared spectroscopy, nuclear magnetic resonance spectroscopy, X-ray diffraction, X-ray photoelectron spectroscopy, Raman spectroscopy, atomic force microscopy, and current-sensing atomic-force spectroscopy.

Work in **modeling** has led to a better understanding of cell performance issues. Models of molecular interactions have led to the understanding of ion transport in an organic solvent and to the optimization of electrolytes. First-principles calculations have led to the understanding of cathode structure and the source of capacity fade. A model is being developed to understand the formation of dendrites at the lithium metal interface.

Other Research

Improved thermal designs for sample cells and modules have been produced and tested. The state-of-the-art design is currently an air-cooled system, but more efficient liquid-cooled battery systems have been analyzed. The latter systems will receive further development and validation.

Battery electrical models have been developed and validated for use in vehicle simulation and target analysis. These models have been used for optimization studies and for evaluation of combined energy storage devices, such as a battery combined with an ultracapacitor.

Finally, FCVT has monitored and managed several Small Business Innovative Research (SBIR) projects related to advanced electrode and electrolyte materials.

Targets

The technical targets established by the energy storage group in close cooperation with the technical teams are provided in Tables 10–12 for the 42V systems [two types: medium-HEV (M-HEV) and power-assist HEV (P-HEV)], HEV systems (two types: power-assist minimum and maximum), and EVs. Table 10 provides proposed targets for a 42V battery, and Table 13 provides proposed targets for a hybrid fuel cell vehicle; these requirements will be refined and adopted by 2005.

The Heavy Hybrid Propulsion activity also requires advanced energy storage systems to meet technology goals. The Energy Storage sub-program will support the Advanced Heavy Hybrid Propulsion activity through the 21st CTP and FreedomCAR and Fuel Partnership technical teams by assisting in the finalization of technical targets and by developing energy storage systems that meet the targets for these vehicles.

Table 10. Energy Storage targets for 42V systems: M-HEV and P-HEV

Characteristics	USABC M-HEV commercialization goals	USABC P-HEV commercialization goals
Discharge pulse power (kW)	13 (for 2 seconds)	18 (for 10 seconds)
Regenerative pulse power (kW)	8 (for 2 seconds)	18 (for 2 seconds)
Engine-off accessory load (kW)	3 for 5 minutes	3 for 5 minutes
Available energy (Wh @ 3 kW)	300	700
Recharge rate (kW)	2.6 kW	4.5 kW
Energy efficiency on load profile (%)	90	90
Cycle life, profiles (engine starts)	150 k (450 k)	150 k (450 k)
Cycle life and efficiency load profile	Partial power assist (PPA)	Full power assist (FPA)
Cold cranking power @ −30°C (kW)	8 (21 V minimum)	8 (21 V minimum)
Calendar life (years)	15	15
Maximum system weight (kg)	25	35
Maximum system volume (liters)	20	28
Self discharge (Wh/day)	< 20	< 20
Maximum operating voltage (Vdc)	48	48
Maximum open circuit voltage (Vdc)	48 (after 1 sec.)	48 (after 1 sec.)
Minimum operating voltage (Vdc)	27	27
Operating temperature range (ºC)	−30 to 52	−30 to 52
Selling price ($/system at a production volume of 100,000 units/year)	260	360

Table 11. Energy Storage targets for hybrid electric vehicle

HEV goals characteristics	Power-assist minimum	Power-assist maximum
Pulse discharge power (kW)	25 (for 10 seconds)	40 (for 10 seconds)
Maximum regenerating pulse (10 s; kW)	20 (50 Wh pulse)	35 (97 Wh pulse)
Total available energy (kWh)	0.3	0.5
Round trip efficiency (%)	>90–25 Wh cycle	>90–50 Wh cycle
Cycle life for specified SOC increments (cycles)	300-k 25-Wh cycle (7.5 MWh)	300-k 50-Wh cycle (15 MWh)
Cold-cranking power at −30ºC (three 2-s pulses, 10-s rests between; kW)	5	7
Calendar life (years)	15	15
Maximum weight (kg)	40	60
Maximum volume (liters)	32	45
Production price @ 100k units/year ($)	500	800
Maximum operating voltage (Vdc)	<400 maximum	<400 maximum
Minimum operating voltage (Vdc)	$>0.55 \times V_{max}$	$>0.55 \times V_{max}$
Maximum self-discharge (Wh/d)	50	50
Operating temperature (ºC)	−30 to +52	−30 to +52
Survival temperature (ºC)	−46 to +66	−46 to +66

Table 12. Energy Storage targets for electric vehicles: 40 kWh			
Characteristics	**Mid-term goal**	**Minimum goals for long-term commercialization**	**Long-term goal**
Power density (W/L)	250	460	600
Specific power—discharge, 80 % DOD/10 sec (W/kg)	150	300	400
Specific power—regeneration, 20 % DOD/10 s (W/kg)	75	150	200
Energy density—C/3 discharge rate (Wh/L)	135	230	300
Specific energy—C/3 discharge rate (Wh/kg)	80	150	200
Power : energy ratio	2 : 1	2 : 1	2 : 1
Total energy (kWh)	40	40	40
Life (years)	5	10	10
Cycle life—80 % DOD (cycles)	600	1000 to 80% DOD, 1600 to 50% DOD, 2670 to 30% DOD	1000
Power and capacity degradation (% of rated spec.)	20	20	20
Ultimate price—10,000 units @ 40 kWh ($/kWh)	150	< 150 ($75/kWh desired)	100
Operating environment (ºC)	−30 to 65	−40 to 50, 20% performance loss (10% desired)	−40 to 85
Normal recharge time (hours)	6	6 (4 Desired)	3 to 6
High rate charge	40–80 % SOC in 15 minutes	20–70 % SOC in <30 minutes @ 150 W/kg (< 20 min.@ 270 W/kg desired)	40–80 % SOC in 15 minutes
Continuous discharge in 1 hour—no failure (% of rated energy capacity)	75	75	75

Table 13. Proposed Energy Storage targets for hybrid fuel cell vehicles (FCVs)		
Hybrid FCV goals characteristics	**Hybrid FCV battery minimum**	**Hybrid FCV battery maximum**
Pulse discharge power (kW)	25 (for 18 s)	75 (for 18 s)
Maximum regeneration pulse (kW)	22 (for 10 s)	65 (for 10 s)
Total available energy (kWh)	1.5	5
Round trip efficiency (%)	>90	>90
Cycle life (cycles)	TBD (15 year life equivalent)	TBD (15 year life equivalent)
Cold-start at −30ºC (TBD kW for TBD min; kW)	5	5
Calendar life (years)	15	15
Maximum weight (kg)	40	100
Maximum volume (liters)	30	75
Production price @ 100K units/year ($)	500	1500
Maximum operating voltage (Vdc)	≤ 440 maximum	≤ 440 maximum
Minimum operating voltage (Vdc)	$\geq 0.5 \times V_{max}$	$\geq 0.5 \times V_{max}$
Maximum self-discharge (Wh/d)	50	50
Operating temperature (ºC)	−30 to +52	−30 to +52
Survival temperature (ºC)	−46 to +66	−46 to +66

Barriers

Batteries can be designed to achieve either a high power-to-energy ratio, as in an HEV, or a moderate power-to-energy ratio, as in an EV. Today, batteries designed for high power-to-energy ratios can deliver 300,000 shallow discharge cycles in a lifetime, and they meet or exceed most of the performance targets. However, larger, energy-dense systems have difficulty meeting the requirement of 1000 deep discharge cycles over the life of the battery. In addition, state-of-the-art batteries meeting some or most of the FreedomCAR and Fuel Partnership performance targets fall short of the cost goals. Technical barriers can be characterized under one of four headings: cost, performance, life, and abuse tolerance. Of these, cost is the overriding factor, and the other three must be pursued with a continual consideration of their impact on battery cost. Each of these barriers is being addressed in collaboration with the technical teams and battery manufacturers.

A. **Cost.** Batteries are typically designed for either high-power or high-energy applications. In the former case, the electrodes are constructed with very high surface area, minimizing the amount of active material in the cell and maximizing the amount of inactive material (such as separator and current collectors). For higher-energy systems, the reverse is true; electrodes are made as dense and thick as possible to maximize the energy density. Therefore, based on the type of technology, the relative costs of the components can vary widely. The major contributors to the cost barrier that will be addressed are the separator, the cathode, and the cost of processing the highly reactive components into a functioning Li-ion battery. Addressing the cost barrier requires identifying the key cost issues (e.g., separators), developing and evaluating lower-cost cell components (electrolytes, anodes, cathodes, and separators) and packaging alternatives, and developing low-cost processing methods for advanced cell material production. All these efforts are being undertaken within the FCVT programs.
B. **Performance.** Systems optimized for different applications may need to meet different performance targets. Several general barriers are limiting performance and will continue to be addressed, including low-temperature performance, high-energy-system performance, and the energy density of ultracapacitors. Low-temperature performance is a fundamental material issue that is being addressed in both the applied battery and long-term research programs.
C. **Life.** Hybrid systems with conventional engines have a life target of 15 years. EVs are expected to achieve a life target of 10 years. Three technical barriers must be overcome to achieve these life goals: accurate life predictions are presently not available, a correlation of life to micro changes is lacking, and the continual introduction of new low-cost battery materials on the open market requires a rapid method of screening those that can meet the life requirements. The calendar life requirement of 15 years is challenging, more so with new low-cost materials and fabrication technology. In addition, mechanisms that lead to poor calendar life are intensified as the temperature of the system increases. This requires additional effort in thermal management and the development of more robust chemistries. Addressing these issues requires identifying the life-limiting mechanisms, investigating and developing materials for advanced cell

components that extend cell life, and developing and validating accelerated life test methods.

D. **Abuse tolerance.** It is critical that any new technology introduced in a vehicle be safe under normal and extreme operating conditions. The specific barriers that will be addressed include abuse tolerance during high-temperature exposure, overcharge conditions, and impact or crush situations. Abuse tolerance studies for advanced batteries focus on investigating failure modes through comprehensive cell testing and diagnostic efforts, screening new abuse-tolerant materials and additives, investigating separators that shut down at elevated temperatures to inhibit thermal runaway by resisting current flow, assessing the behavior of vehicle-size modules under abusive conditions, and developing and evaluating technologies to mitigate abusive conditions such as overcharge and overheating.

Approach

The approach to overcoming the technical barriers must be tailored to the needs of the automobile industry. As mentioned, these needs are quite broad, ranging from relatively small 42V systems that would be adequate for a vehicle designed to operate in a minimum "start/stop" mode, to the moderate-size, high-power systems for use in HEVs and hybrid fuel cell vehicles, to the large batteries needed for EVs. These needs will not be met with a single battery and may not be met with a single battery chemistry. FCVT continuously reaffirms the performance and cost targets for the full range of these batteries and develops hardware for specific applications that can be tested against respective performance targets and used for subsystem benchmarking.

In response to these needs, a range of tasks are implemented, from hardware development with industrial contractors to mid-term R&D and long-term research. The tasks begin with the establishment of technical requirements by FCVT in cooperation with industry. Next, batteries available in the marketplace are evaluated against these requirements. If the requirements cannot be met, additional R&D is undertaken, consisting of either short-term directed research (applied research), or more long-term exploratory research.

In all cases, the R&D is directed at overcoming specific technical problems so that the needs of the automotive industry are met. The R&D activities leverage the efforts of many parts of the electrochemical community, including universities, national laboratories, and small and large businesses.

General focus areas. The following are specific tasks that FCVT is currently focusing on and plans to continue developing over the next several years.

- Establish and reaffirm the Fuel Cell and Systems Analysis technical teams' performance targets for batteries for 42V hybrid, hybrid fuel cell, and EV systems. The performance targets include those for power density, specific power, specific energy, cycle and calendar life, cost, and various parameters for operating ranges (e.g., temperatures).
- Perform independent validation testing of promising battery technologies. Examples include, but are not limited to, benchmarking Li-ion/manganese spinel chemistries against HEV and EV targets.

- Establish projects with battery suppliers to develop batteries for validation testing against the technical targets. Examples of such projects include Li-ion full system and Li/S technologies.
- Focus the applied battery research activity on immediate technical barriers (some of which are identified in the previous steps) that inhibit the attainment of established performance and cost targets for batteries. An example includes the development of an accelerated life test to help manufacturers measure the lifetimes of their technologies.
- Manage the long-term battery research activity to address fundamental problems impeding the development of advanced batteries, develop and evaluate novel battery materials, and broaden advanced diagnostic and modeling capabilities. A specific task includes research into cathode materials such as low-cost, stable, and abuse-resistant $LiFePO_4$ and high-voltage, high-capacity $LiNi_xM'_yMn_{1-x-y}O_2$.

The energy storage sub-program includes two go/no-go decisions, both of which are part of the applied battery research task described later in this section. The two go/no-go decisions include these:

- Determining if the Li/S battery meets the electric vehicle cycling requirement (1000 deep discharge cycles).
- Determining if the Li-ion polymer battery meets the HEV life requirements of 15 years and 300,000 cycles.

The calendar-life and cycle-life requirement have been established by DOE and the Electrochemical Energy Storage technical team. High-energy batteries are considered to be at the end of life when they suffer a reduction to 20% capacity or power fade. High-power batteries are considered to be at the end of life when they are no longer able to deliver 25 kW in an 18-s discharge or their net available energy is less than 300 Wh. The established cycle-life and calendar-life test procedures (published by the USABC) will be used to verify that the requirements are met.

As part of FCVT's management of its sub-programs, periodic reviews are conducted to ensure that work is appropriately focused. For example, merit reviews before an independent panel of battery and automotive experts are held to assess the quality and relevance of the work.

Task Descriptions

To implement this approach, specific tasks, described in Tables 14–17, have been identified under the battery development, applied battery research, long-term exploratory research, and other research activities.

Battery Development

FCVT works closely with the car makers through the FreedomCAR and Fuel Partnership Electrochemical Energy Storage technical team in carrying out all of the technical tasks, particularly in the development area. The tasks planned in development are shown in Table 14.

Table 14. Tasks for Battery Development		
Task	**Title**	**Duration/ barriers**
1	Establish Targets, Benchmark and Assess Technologies, and Assess Ultracapacitors • Establish and maintain technical targets for the 42V system, HEV, EV, hybrid fuel cell vehicle, and heavy-duty hybrid batteries. This is a critical step because it provides the R&D community clear goals for their work. The targets that have already been determined are presented earlier in this section • Pursue the continuous evaluation of available technology. Evaluate new technologies and commercial products as they become available, and combine data from these studies with similar data from other development contracts to identify areas for additional R&D • Assess technologies based on the results of current benchmark testing and a thorough review of other available data. If the assessment is positive, begin development with an established manufacturer, potentially to support application to heavy-duty hybrid vehicles	120 months Barriers A,B,C,D *(begin 1Q 1999)*
2	Develop 42V Battery, Issue Solicitation for FCV Battery Development, Develop Li-ion/ Gel Polymer Battery, and Develop Li/S Technology • Based on cost and the ability to meet performance targets, increase the emphasis of the Electrochemical Energy Storage technical team on the development of 42V systems and reduce the emphasis on high-voltage batteries for HEVs • Prepare and publicly advertise a solicitation to attract qualified battery developers to develop hardware for validation testing against hybrid fuel cell vehicle targets • Initiate plans with a qualified developer to further investigate the feasibility of an Li-ion/gel polymer system, a leading candidate for meeting all FreedomCAR and Fuel Partnership targets, including safety. This task involves the go/no-go decision of determining if Li-ion polymer meets the life requirement by 12/31/06 • Because Li/S shows great promise as a high-energy battery couple, and its continued evaluation and development are critical to the success of high-energy storage systems, focus on addressing the lithium/sulfur isolation issue through the development of new processes to protect the lithium anode. Then evaluate these processes and choose one developer to continue development of the most promising technology. Determine if Li/S meets the cycling requirement by 11/30/2006, a go/no-go decision point	84 months Barriers A,B,C,D *(begin 1Q 2003)*

Applied Battery Research

This activity addresses critical, cross-cutting barriers impeding the adoption of technologies that are close to commercialization. Specific tasks are presented in Table 15.

Long-Term Exploratory Research

The long-term exploratory research activity consists of research on new electrochemical systems that have the potential to meet the technical targets. The emphasis is on understanding fundamental processes and limitations and using this knowledge to develop new and improved materials and components. This work requires a steady, focused, long-term commitment.

Baseline systems for exploratory research are defined to help maintain a level of cohesiveness and provide continuous focus to the investigators. Specific task details are shown in Table 16.

Table 15. Tasks for Applied Battery Research		
Task	**Title**	**Duration/ barriers**
3	Screen Materials, Study Power Fade, Study Overcharge, Improve Abuse Tolerance, and Develop Advanced System • Rapidly screen and evaluate new materials being offered by vendors by using advanced diagnostic techniques to determine whether they meet performance and life targets. Disseminate results of the screening to the battery community through formal reports and quarterly reviews • Apply a range of diagnostic techniques to a group of cells aged to various degrees in order to determine the exact cause of power fade in cells designed for high-power applications • Expose cells designed specifically for high-power applications to overcharge and high-temperature conditions to increase understanding of the chemical processes occurring that may result in thermal runaway and cell failure • Evaluate additives, coatings, and new active materials designed specifically to mitigate the effects of exposure to overcharge and/or high temperatures • Pursue work under way to define an advanced electrochemical system with lower cost, higher stability, and improved low-temperature capability. This is being done through advanced electrolyte modeling, advanced anode screening and development, and electrochemical testing and diagnostics	132 months Barriers A,B,C,D *(begin 1Q 1999)*
4	Develop Accelerated Life Testing Protocols, and Evaluate Enhanced Quality Control • Validate and publish by the end of 2005 a robust Accelerated Life Testing protocol that will provide the battery industry with a statistically accurate prediction of cell life within a short time period. This protocol is to be user friendly to encourage rapid adoption by battery developers • Undertake a diagnostic effort to address issues related to cell-to-cell reproducibility, material handling, and quality control procedures during electrode manufacturing. This diagnostic effort will lead to more cost effective cell production and lower unit cost	120 months Barrier B,C *(begin 1Q 1999)*

Table 16. Tasks for Long-Term Exploratory Research		
Task	**Title**	**Duration/ barriers**
5	Define Baseline Chemistry, Assemble and Test Baseline Cells, Conduct Diagnosis and Modeling, and Synthesize and Evaluate Novel Materials • Review the baseline and exploratory systems every 2 to 3 years and revise them as needed to provide direction and cohesiveness to investigators • Assemble materials acquired from the Anodes, Electrolytes, and Cathodes areas or from outside sources into laboratory cells and test them (Cell Development group) • Examine virgin materials, as well as materials from uncycled and cycled cells, to determine failure mechanisms (Diagnostics group). Model the baseline systems and optimize the design of each system for applications where each system is more likely to meet performance targets. Model growth of the surface-electrolyte interface layer, structural changes during cycling, and ohmic losses due to poor particle-to-particle contact (Modeling group) • Synthesize novel materials offering the possibility for improved cell performance, life, or cost (Anodes, Electrolytes, and Cathodes group). Research on polymers may shift to gels where significant cost savings can be achieved.	120 months Barriers B,C,D *(begin 1Q 2001)*

Other Research

Other activities carried out by FCVT that are not exclusive to one of the preceding activities are presented in Table 17. These tasks include the modeling of thermal properties, development of both battery and full system models, and ongoing participation in SBIR.

Table 17. Tasks for Other Research

Task	Title	Duration/ barriers
6	Model and Measure Thermal Properties, Develop Battery System Models, Conduct Simulations, and Participate in the SBIR Program • Measure thermal characteristics of batteries. Model the thermal performance of batteries and use computer-aided design tools to develop configurations with improved thermal performance. Give special attention to 42V batteries for three classes of HEVs and to hybrid fuel cell systems. The effectiveness of high-frequency ac to preheat batteries at very cold temperatures is under study • Task engineers to work with battery developers to improve and validate energy storage models for system simulations. Researchers will use these models in optimization studies and target analyses for different platforms and vehicle types • Prepare SBIR topics each year, focusing on innovative technologies that stand a reasonable chance of technical success and market penetration. Subject to the availability of SBIR funding, publish these topics, review proposals, and make grants to the best proposals. This is an extremely valuable method for DOE to fund small, low-cost, high-risk research that promises to revolutionize the battery industry	108 months Barriers B,C *(begin 1Q 2002)*

Milestones

The task-level milestones showing the Energy Storage Group's plans for the next several years are shown in the network chart. The formal milestones exclude those concerned with managing tasks (e.g., holding merit reviews and changing the direction of work based on developer needs).